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Greenhouse Gas Mitigation Options For Washington State

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Washington State Greenhouse Gas Emission Reduction Strategies

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Disclaimer

…people can not imagine geologic time. Human life is lived on another time scale entirely. An apple turns brown in a few minutes. Silverware turns black in a few days. A compost heap decays in a season. A child grows up in a decade. None of these everyday experiences prepares people to be able to imagine the meaning of eighty million years…

—Michael Crichton, Jurassic Park

…*Does a climate exist?* That is, does the earth's weather have a long term average? Most meteorologists...took the answer for granted. Surely any measurable behavior, no matter how it fluctuates, must have an average. Yet on reflection, it is far from obvious. As [Edward] Lorenz pointed out, the average weather for the last 12,000 years has been notably different than the average for the previous 12,000, when most of North America was covered by ice. Was there one climate that changed to another for some physical reason? Or is there an even longer-term climate within which those periods were just fluctuations? Or is it possible that a system like the weather may never converge to an average?

—James Gleick, CHAOS Making a New Science

Author's Note

Writing about global warming is a difficult task for many reasons. First, the science is rapidly evolving and with it our understanding of the world's climate system. During the writing of this report, it seemed that every few days new estimates would emerge on temperature changes, storm intensities, spatial ranges of diseases, or changes in agriculture yields and forestry production. In this situation, one difficulty lies in the decision to stop researching and start writing. Certainly, some aspects of this report were out of date even before it was completed.

A second difficulty lies in the enormous scope of the science. Global climate change could potentially affect virtually all aspects of human society and the environment. As such, a vast and growing climate change library covers everything from changes in water resources to the prevalence of extreme weather events to the comparative advantage of various species of subterranean biota. For the most part, information included in the report came from peer reviewed articles, government reports and books published after 1990. I reviewed several hundred potential information sources -- more than 100 of which made their way into the report as references. Nevertheless, this number constitutes only a small proportion of the information available on climate change. Inevitably, reports containing important information on climate change were overlooked.

A final difficulty is the often conflicting conclusions of scientists regarding the consequences of climate change. For example, Rosenzweig reports optimistic prospects for agriculture)at least in the developed world) under global climate change while Bazzaz appears rather less sanguine. Such conflicting reports allow for many different assessments regarding the consequences of climate change. My reading of the scientific record could not support a conclusion that suggests that climate change poses a substantial threat to Washington state over the next 80 to 100 years. Indeed, to my mind, the consequences appear significant but relatively small in magnitude. However, other interpretations of the record are equally valid as are other conclusions regarding the threat to this State posed by climate change.

EXECUTIVE SUMMARY

President Clinton, in 1993, established a goal for the United States to return emissions of greenhouse gases to 1990 levels by the year 2000. One effort established to help meet this goal was a three part Environmental Protection Agency state grant program. Washington State completed part one of this program with the release of the 1990 greenhouse gas emissions inventory and 2010 projected inventory.(1) This document completes part two by detailing alternative greenhouse gas mitigation options. In part three of the program EPA, working in partnership with the States, may help fund innovative greenhouse gas reduction strategies.

The greenhouse gas control options analyzed in this report have a wide range of greenhouse gas reductions, costs, and implementation requirements. In order to select and implement a prudent mix of control strategies, policy makers need to have some notion of the potential change in climate, the consequences of that change and the uncertainties contained therein. By understanding the risks of climate change, policy makers can better balance the use of scarce public resources for concerns that are immediate and present against those that affect future generations. Therefore, prior to analyzing alternative greenhouse gas control measures, this report briefly describes the phenomenon and uncertainties of global climate change, and then projects the likely consequences for Washington state.(2)

Global climate change poses daunting public policy problems. According to some the consequences will be nothing short of apocalyptic: world wide famine, epidemics, massive flooding, and more violent storms. To others, the consequences are minimal and perhaps even beneficial in specific areas like agriculture. The divergence of opinions reveals the limitations in our understanding of the global environment and climate system. Scientists agree that continued consumption of fossil fuels will elevate greenhouse gas levels in the atmosphere. Most also agree that higher greenhouse gas concentrations will raise average global temperatures—though they debate its magnitude and timing. This agreement breaks down when predicting secondary effects like precipitation, soil moisture, storm severity and flooding. A limited understanding about how flora and fauna may respond to climate change further compounds the uncertainty. Despite these uncertainties, policy makers need to know the potential threats and uncertainties posed by climate change if they are to develop well reasoned policy responses.

Based on work by the Intergovernmental Panel on Climate Change, this report assumes that doubling pre-industrial levels of atmosphere greenhouse gases (somewhere between the years 2060 and 2090) will raise temperatures in Washington by 2·C (about 4·F) and will not change average precipitation levels. This report analyzes the Human Health, Agriculture, Forestry, Fisheries, Power Production, Sea-Level Rise and Economic effects of such changes. With the exception of sea-level rise, the consequences of the presumed climate changes appear relatively mild in Washington. However, one important limitation of this report is that each area (e.g., human health) was analyzed independently. Interactions between areas could result in outcomes significantly different than predicted here. Moreover, atmospheric greenhouse gas levels will grow beyond twice pre-industrial levels. Thus, the consequences for Washington could be greater further in the future.

Projected Consequences of Climate Change

Health Effects: A 2·C temperature change will not likely have severe adverse affects on the health of Washington citizens (the temperature extremes would still be well below those presently occurring in other areas of the country). Further, a 2·C temperature change is not likely to bring important tropical diseases to Washington.

Agricultural: Agriculture may actually benefit from the climate change. The primary greenhouse gas, carbon dioxide, is an essential plant nutrient. A 2·C temperature rise may expand the growing season and is well within the tolerance limits of most cash crops. EPA reports that agriculture acreage in the Pacific Northwest could increase 5 to 17 percent as a result of climate change. However, irrigation requirements may also increase.

Forestry: Climate change may alter the comparative advantages between tree species and thus change the climax species of an area. Forests may expand into some currently inhospitable environs and withdraw from others. However, since trees are long-lived, these shifts may not be noticeable for many years. The carbon dioxide fertilization effect may somewhat mollify the effects of climate change. The risk of forest fires will also increase with climate change. Warmer temperatures would dry out forests, lengthen the fire season and increase both the area burnt and number of forest fires.

Fish: Climate change will likely affect fish resources through changing rainfall/snow melt patterns. One study of 60 Pacific northwest salmonoid subspecies found climate change to adversely affect 14 species, to not affect 24 species and to benefit 21 species. However, given the critical condition of many fish species climate change may ultimately introduce more stress on fish stocks already depleted due to other environmental factors.

Energy: Energy production in the Pacific Northwest is vulnerable to climate change due to our heavy reliance on hydroelectric power. With constant precipitation and a lower snow pack volume (from warmer temperatures) winter and spring river flow will increase. Earlier spring runoff may ease supply constraints during the period of highest demand. Conversely, lower summer and fall flow would degrade water supply reliability. Warmer temperatures will lessen wintertime demand for heating but increase summertime cooling demand.

Sea-Level Rise: Climate change is estimated to raise sea-levels by about 1.3 feet through 2100. Motions of the earth's crust complicate the effect of sea-level rise. Washington's coast is currently rising relative to the ocean. Uplift should roughly equal the projected sea-level rise along northern and southern coasts. Over the mid-coastal area, the sea level may rise a foot or more. Along inland waters the sea level may rise 1 foot in the northern Puget Sound and 1.5 feet in south Puget Sound.

Economy: The effects of climate change on Washington's economy do not appear significant. The economic sectors that are potentially most affected by climate change—agriculture, forestry and fisheries—account for about 8 percent of the state's economy. And agriculture and forestry may actually do better under climate change. Moreover, continued expansion of the service sector should lower the portion of the economy at risk to climate change. However, exports are an important part of Washington's economy. Climate change could reduce the foreign customers ability to purchase Washington state goods and services.

It is important to remember that our understanding of the global climate system is limited. Thus, the projected consequences of climate change are speculative and will change as we learn more about the global climate system. For example, estimates of sea-level rise have gone from 10 meters to less than one meter. In addition, surprises—good and bad effects beyond our ability to predict with current knowledge—are possible (or even probable) as climate, environments, and species interact and adapt in unexpected ways. Beyond these considerations are uncertainties about the rate carbon dioxide is added to the atmosphere. Advances in combustion turbine technology, for example, have lowered carbon dioxide emissions per unit of electricity produced by 70 percent relative to traditional coal fired power plants. The Administration also is sponsoring a research effort to triple the fuel efficiency of motor vehicles. The success and application of such efficiency technologies (or lack thereof) will have a huge effect on the magnitude and timing of climate change. Thus, the reported climate change projections and the consequences thereof may reasonably describe what will occur or may be completely wrong.

Uncertainties about the consequences of climate change create a dilemma. Years to decades will pass before uncertainties about climate change are resolved. Waiting risks irreversible damages while immediate action risks large expenditures to mitigate inconsequential or even beneficial changes. There are several ways policy makers might approach this balancing effort. One is to consider greenhouse gas mitigation measures as insurance against uncertain risks. Following this logic results in an active greenhouse gas control program to reduce our risks until knowledge about climate change improves. Another approach is to invest heavily into research and development in technologies with the potential to reduce greenhouse gas emissions. A third approach is to implement only those activities that make sense for reasons beyond climate change—a "no regrets" approach. Determining the appropriate government response to climate change requires the skills of both scientists and policy makers; scientists to describe potential consequences and policy analysis to balance the potential threats and opportunities of climate change against other social needs and desires.

For Washington to stabilizing greenhouse gas emissions—President Clinton's goal—requires an 18 million ton reduction from "business as usual" in the year 2010. The transportation category emits the most carbon dioxide and therefore is the largest emission reduction target. Industrial and utilities are the next two emission categories followed by the residential and commercial sectors. No single activity in Washington dominates carbon dioxide emissions, and therefore, no single measure can stabilize this state's greenhouse gases. Significant reductions in greenhouse gas emissions will require a broad range of mitigation programs.

Table 1 lists the mitigation strategies evaluated in this report that cost less than $100 per ton of greenhouse gas controlled. The reduction and costs estimates required many assumptions about society in the year 2010. Small errors compounded over time (e.g., fuel consumption patterns), or large errors in technology assessment (e.g., the introduction of residential fuel cells) could easily upset these figures. Nonetheless, the estimates are reasonable given what we know today. About three-fourths of the carbon dioxide reductions necessary to achieve the President's goal have low costs. "No regrets" options could reduce emissions by 8 million tons. They include upgrades to building codes and efforts to alter building operating practices. Measures costing less than $5 per ton reduce emissions another 5.6 million tons, principally through afforestation. Further reductions are more expensive. A $1.00 per gallon gasoline tax, for example, could eliminate 8.5 million tons of carbon dioxide at a cost of about $15 per ton.

Table 1 Alternative Greenhouse Gas Mitigation Strategies

Strategy	Potential Annual Emission Reductions in 2010 (Tons)	Cost per Ton Reduced
Residential Sector		
EXISTING HOME RETROFITS		
Direct Use of Natural Gas in Buildings	250,000	+
R-19 Attic for Electrically Heated Homes	209,000	+
R-11 Wall for Homes	113,000	+
R-19 Floor for N.G. Heated Homes	105,000	+
R-30 Attic for N.G. Heated Homes	15,000	+
Low Flow Shower Head	7,000	+
Hot Water Tank Upgrade (N.G.)	4,000	$3
R-11 Duct Insulation For N.G. Homes	11,000	$16

Caulking Joints in N.G. Homes	5,000	$33
Install Fluorescent Lighting in Buildings	460,000	?
NEW HOME BUILDING PRACTICES		
Class 35 Windows Code	106,000	+
R-30 Floor Code for N.G. Homes (Zone 1)	17,000	$59
R-38 Attic Code for N.G. Homes (Zone 1)	6,000	$74
R-21 Walls Code	25,000	$78
Commercial Sector		
Efficient Fluorescent Lighting Retrofits	5,400,000	+
More Efficient Food Refrigeration	550,000	+
A variety of Efficiency Improvements for Public Sector Commercial Buildings	438,000	+
Industrial Sector		
Petroleum Refining Process Improvements	134,000	?
Pulp and Paper Process Improvements	1,049,000	?
Aluminum Process Improvements	1,184,000	?
Transportation Sector		
Tire Pressure Check	35,000	+
More Efficient Airplane Engines	800,000	+
FeeBate ($100/MPG off baseline)	4,400,000	~$0
Gas Tax ($1.00/gallon)	8,500,000	$15
Vehicle Mileage Tax ($0.04/mile)	8,200,000	$45
Parking Restrictions	?	$?
Diesel to Electric Train Conversion	220,000	$?

Truck to Train Mode Shift	1,680,000	$?
Generating Resources		
Chemical Boiler Cogeneration	410,000	+
Landfill Gas Combustion	494,000	~$0
Animal Manure	110,000	$2
Nuclear Power (extend WNP-2)	2,960,000	$25
Wood Waste Combustion	150,000	$80
Agricultural Waste Combustion	282,000	$93
Wind	450,000	?
Carbon Sequestration		
Afforestation	5,500,000	$4

† The cost per ton based on carbon dioxide equivalent reductions. (See Global Warming Index sidebar.)
A "+" indicates a net benefit—the efficiency measure's costs are completely offset by reduced energy expenditures.
A "?" denotes uncertain costs. The reduction estimates are not additive (e.g., interactions between strategies may result in an over estimate of the actual result if added together). Moreover, the number of alternatives reviewed prevented detailed review of individual programs. Therefore, the numbers presented above are preliminary. See the body of the report for a more detailed explanation of each mitigation strategy, and its associated emission reduction and cost.

INTRODUCTION

Global climate change poses daunting public policy problems. Since humans first effectively harnessed the energy within coal and oil, a myriad of new technologies and machinery have saved inestimable amounts of labor and vastly improved living standards. We dwell and work in large homes and buildings which are warm in the winter and cool in the summer, we routinely travel great distances and we have access to a wide array of consumer goods. And yet the principal power source supporting this living standard may threaten the world community. Fossil fuels emit carbon dioxide when burned. Over the past 100 years, carbon dioxide levels in the atmosphere increased 25 percent. Carbon dioxide concentrations will continue to increase as the world population grows and societies around the globe industrialize.

Within the scientific community there is near unanimity of opinion that adding carbon dioxide and other greenhouse gases to the atmosphere will alter the Earth's climate. The great debate and uncertainty is over how much and how rapidly the climate will change, and how that change will affect flora, fauna, and human society. Depending upon the speaker, the projected effects of climate change range from apocalyptic to desirable. The divergence of opinions reveals our limited knowledge and understanding of how the climate system works. Even more uncertain are regional changes in important climate parameters like temperature, soil moisture, precipitation, storm severity and flooding. Understanding how climate change might affect these parameters is extremely important as flora, fauna and human society are sensitive to them all.

Compounding the scientific uncertainties are the economic costs of greenhouse gas mitigation programs. Estimates of the cost of stabilizing greenhouse gas emissions at 80 percent of their 1990 levels range from essentially no cost up to a permanent and re-occurring 3 percent loss in U.S. Gross National Product. The uncertain consequences of climate change along with potentially high mitigation costs makes developing and implementing an appropriate response extremely difficult. Oates and Portney summarize the scientific and policy difficulties associated with global climate change as follows:

> *It is hard to imagine a policy problem more daunting than global warming. To begin with, we are not sure what we are up against. The problem is shrouded in uncertainties of the most difficult sort. Actions today to reduce emissions of greenhouse gases will have their effects on global climate many years down the road, and the magnitude and timing of these effects are the subject of much dispute. Point estimates of possible changes in temperature, rainfall, and other dimensions of global climate come with large confidence intervals, and the estimates are themselves often based on relatively simplistic extrapolations that do not allow for potentially frightening changes in climate should we set off processes of which we are currently unaware. Our imperfect knowledge has led to sharply contrasting policy positions: at one extreme are those suggesting that we wait until we have a firmer understanding of the global warming process before adopting costly preventive measures; at the other are those urging rapid action to forestall some possibly catastrophic outcomes.*
>
> *But uncertainty is not the only aspect of global warming that makes it so difficult to address. Effective policies to reduce emissions of greenhouse gases are likely to be very expensive. William Nordhaus [1991], for example, estimates that the cost of cutting greenhouse gas emissions in half, if done efficiently on a worldwide scale, would be on the order of 1 percent of world output, and could easily cost more. We could find ourselves in the United States spending as much on such*

> *policies as we spend on all other efforts to control pollution combined! Moreover, global warming is an international public good. Emissions from one country are essentially a perfect substitute for emissions elsewhere. The issue then is one of total planetary emissions of these gases. And no one country is of sufficient size to "go it alone." Effective policies to address global warming will have to be international in scope--they must enlist widespread participation if there is to be any hope of success.*
>
> --Bill Oates and Paul Portney

Climate change is disquieting precisely because of what we do not know: its magnitude, timing and the range of consequences. Further, present day decision-makers will be long dead before the consequences are known. The scientific uncertainties and mitigation costs leave policy makers with a conundrum. On the one hand, failure to act may hasten the onset of severe climate effects. On the other hand, an investment of vast resources may prevent an insignificant or even beneficial climate change. As such, policy makers need the wisdom of Solomon to devise a response that balances present day economic growth and prosperity with the future environment. While this report makes no claim to impart such wisdom, it should provide policy makers with some notion of the key uncertainties of climate change, the potential effects in Washington state and the measures available to lower greenhouse gas emissions. Policy makers need such information to balance present day social and economic needs with the potential harm caused by climate change to future generations and the environment

To this end, this report begins with a description of current knowledge and key uncertainties about the greenhouse effect. This section includes a discussion of the magnitude and timing of anticipated changes in important climate parameters. This section then speculates about the effect of these climate changes on Washington State. The second section of this report projects the State's greenhouse gas emissions inventory for the years 1990 and 2010. Next is a description of various options available to reduce emissions of greenhouse gases. Whenever possible, estimates of the carbon dioxide reduction potential and economic costs of each option are included. The report concludes with a discussion of alternative approaches policy makers might follow to develop a response to global climate change.

The Radiation Budget

The radiative budget is a term used by scientists to track energy flows in the atmosphere. It basically works as follows: Incoming solar radiation has an energy of 340 Watts per square meter (W/m2) of which 100 W/m2 is reflected back into space (from ice, snow and clouds). The remaining 240 W/m2 warms the earth to -18·C. The earth's surface radiates 420 W/m2. The atmosphere absorbs a large fraction of the of the 420 W/m2 and re-radiates 180 W/m2 back to earth. This raises the Earth's temperature to about 15·C. Doubling pre-industrial atmospheric carbon dioxide (CO2) levels would increase the energy reflected back to earth by about 4 W/m2. However, while it is relatively easy to predict how atmospheric changes affect the radiation budget, estimating a temperature and climate response is much more difficult.

THE GREENHOUSE EFFECT

All celestial bodies radiate energy. The wavelength of the radiated energy is inversely related to the temperature of the celestial body. The hot sun emits short wavelength radiation that easily passes through the Earth's atmosphere. The relatively cool Earth radiates long wavelength infrared energy. Atmospheric gases such as water vapor, carbon dioxide, methane, nitrous oxide, and ozone can "intercept" some of this infrared energy and re-radiate it in all directions. The portion directed downwards further warms the Earth. This phenomenon, known as the greenhouse effect is a vital part of Earth's climate. The earth would be some 30 degrees Celsius colder were greenhouse gases absent from the atmosphere.

Climate change has become a concern because of increasing levels of greenhouse gases in the atmosphere. Over the last 100 years fossil fuel consumption (e.g., the burning of coal, petroleum products and natural gas), deforestation and industrial activity has elevated carbon dioxide levels from 280 to 350 parts per million; methane concentrations from 0.8 to 1.7 parts per million; and nitrous oxide levels from 288 to 310 parts per billion. These additional greenhouse gases portend a stronger greenhouse effect and a warmer earth. In fact, the Intergovernmental Panel on Climate Change (IPCC, 1992) concluded that the global mean temperature has increased 0.3 to 0.5·C since the 1880s.(3)

Attributing this rise in temperature to a specific cause is very difficult. Scientists predict the effect of increased greenhouse gas concentrations on the global climate with computer global circulation models (GCMs). While scientists are improving the physical realism of these models, shortcomings remain. Perhaps most important is that several important climate feedbacks are only partially understood. For example, alone, a doubling of carbon dioxide levels would raise temperatures less than 1·C. GCMs presume that a carbon dioxide induced temperature rise will increase atmospheric water vapor—a potent greenhouse gas—and magnify the climate change. However, the magnitude of the water vapor and other feedbacks is the subject of much scientific debate and active research. (See sidebar). Despite this and other shortcomings, GCMs do represent the global climate system reasonably well and in any case are the best predictive tool available.

Furthermore, knowledge about how the climate system works continues to grow. For example, chlorofluorocarbon gases were once thought significant greenhouse gases (a 0.6 W/m2 increase in radiative-forcing) but are now assumed to have no net effect. Though potent greenhouse gases, they destroy stratospheric ozone, another global warming gas. The decrease in global warming potential from stratospheric ozone depletion is thought to offset the radiative-forcing contribution of chlorofluorocarbons. Therefore, GCM predictions that include the radiative forcing of chloroflourocarbons systematically overstate warming.(4)

A second example of improved understanding about the climate system concerns the cooling effects of sulfur dioxide pollution. Once in the atmosphere, sulfur dioxide transforms into sulfate aerosols. These aerosols intercept some sunlight before it reaches the earth and reflect it back into space. The cooling effect of sulfate aerosols may reach 1 W/m2 (Charlson). Efforts to control sulfur dioxide emissions will lower the cooling effect of this pollutant.(5)

After considering these and other developments, the IPCC recently concluded that recent changes in global temperature were *"…unlikely to be entirely due to natural causes and that a pattern of climatic response to human activities is identifiable in the climatological record."* (IPCC, 1995). As this IPCC conclusion indicates, little debate remains over the physics of global warming. Most agree that elevated greenhouse gas levels will raise temperatures and alter the climate.(6) However, projecting the magnitude and timing of the change is very complicated. A basic element of this projection is the rate at which greenhouse gas concentrations increase. The four GCMs presented in the 1992 IPCC supplemental report model a doubling of greenhouse gas concentrations in 70, 60, 100 and 170 years. This is a heroic

Climate Feedbacks

A climate feedback is any mechanism that amplifies or diminishes the effect of the original change in the system. In addition to water vapor, other important climate feedbacks include:

- Snow-Ice Albedo: Snow and ice reflect light (albedo) and lower temperatures. Warming induced ice/snow recession would decrease light reflection and intensify warming. If, however, climate change increases polar precipitation (as some GCMs project) snow/ice at the poles may expand, reflect more light and slow warming.
- Cloud: The cloud feedback is large, complex and poorly understood. Clouds are though to have a net cooling effect, depending on latitude and water content If cloud formation increases with global warming (due to increased evaporation) a cooling feedback may occur.
- Ocean: Ocean storage of CO2, depends on temperature and physical behavior (ocean currents). Ocean feedback is usually thought to accelerate global warming, however, regional responses are poorly understood.
- Methane: Warmer temperatures speed the chemical transformation of methane into less potent CO2 Warming may also increase methane releases from oceans. The resulting feedback from these opposing effects is uncertain.

assumption since scientists cannot even balance the present day carbon cycle. After subtracting ocean uptake and atmospheric loading from fossil fuel and terrestrial emissions, some 1.2 metric gigatons (approximately 1.4 billion short tons) of carbon dioxide remain unaccounted for (Tans, Douglas). Some recent research suggests that a combination of uptake by Northern Hemisphere forests and carbon deposition account for the missing carbon (Schimel, Culotta).

Another difficulty in predicting long-term climate change is fluctuations in atmospheric carbon dioxide loading. Most GCMs assume a linear or exponential increase in greenhouse gas levels. However, actual loading is very much more variable. Conway et. al., report that carbon dioxide loading fell from almost 5 gigatons per year to less than 2 gigatons per year between 1987 and 1992. (This indicates the variability of atmospheric carbon loading; it does not signify a downward trend.) Francey et. al. attributes much of the recent change to a strong El Niño event.(7)

The amount of carbon dioxide added to the atmosphere also depends on carbon cycle feedbacks. Temperature, precipitation, vegetation distribution, land use and atmospheric carbon dioxide levels all affect terrestrial systems carbon uptake. Secondary factors include increased ultraviolet radiation, eutrophication, and pollution on terrestrial and aquatic ecosystems. Francey reports that ocean and terrestrial uptake can each annually vary up to 2 gigatons of carbon dioxide. Presently, our understanding of the implications of carbon cycle feedbacks is lacking (Chameides). Therefore, while it is generally agreed that greenhouse gas levels will rise over time, considerable uncertainty remains as to how quickly this will occur.(8)

Finally, it is important to remember that regional climate changes can vary significantly from global averages. Moreover, seasonal changes in precipitation, soil moisture, sea level and storm severity are likely to be very important consequences of climate change. As a result, uncertainties abound when predicting the consequence of climate change for a region.

THE EFFECTS OF GLOBAL WARMING IN WASHINGTON STATE

Prior to discussing the potential effects of global climate change on the Pacific northwest, we examine changes in temperature and

Computer Climate Model Limitations

Computer climate models are derived from weather-forecasting programs. They have many built-in assumptions based on past weather and climate. Fundamentally different conditions, like elevated CO2 levels, may invalidate those assumptions.

Computer power also limits GCMs. As such they simplisticly represent climate. For example, many hold that the oceans drive much of world climate (Rahmstorf). Unfortunately, both our understanding of ocean behavior and GCM modeling of atmosphere/ocean precipitation in Washington since 1900. Figure 1 reveals that temperatures across the state increased through the 1930s and, despite substantial year-to-year variation, held steady on average thereafter.(9) (There does, however, appear to be an increase in minimum temperatures since the 1950s.) In western Washington, average annual temperature typically varies about 0.5·C between years and changes over 1.0·C are not uncommon. Eastern Washington experiences higher inter-annual variation; averaging 0.7·C and ranging up to 1.5·C. This figure does not indicate whether changes in seasonal temperatures occurred.

interaction are wanting. Climate models also do not deal well with chaotic behavior; unexpected variations in wind/ocean behavior can significantly alter climate predictions.

Figure 2 presents precipitation levels across Washington. Although quite variable, rainfall appears to have changed little over the past 90 years. However, between years rainfall changes average more than 15 percent (both increasing and decreasing) and changes over 35 percent have occurred. Together, the temperature and precipitation profiles in Washington indicate a climate prone to relatively large swings in character. The effects of global climate change must be considered against this natural variability.

Figure 1 (unavailable at this time)

Figure 2 (unavailable at this time)

The assessment of climate change in Washington is based on data presented in the 1992 IPCC supplemental report. The IPCC report details climate response predictions of four coupled ocean-atmospheric GCMs to a transient doubling of carbon dioxide. One model indicates temperatures will rise less than 1·C for the Pacific Northwest-British Columbia region; two predict temperatures 1-2·C warmer; the fourth models a 2-3·C temperature increase. Perhaps even more important, the GCMs indicate little change in average rainfall and only a slight decrease in soil moisture.(10)

While acknowledging the uncertainty regarding any climate change prediction, this report assumes that the IPCC is the best judge of an estimate's credibility. Therefore, based on the data from the IPCC report, the report assumes a 2·C rise in temperatures in Washington as a result of a doubling of effective carbon dioxide levels in the atmosphere. In addition, average precipitation levels are assumed not to change. These predictions form the basis for assessing how climate change might affect Washington State.(11)

When discussing the potential effects of global climate change in Washington, it is important to remember that the uncertainties inherent in global climate change predictions are amplified in the regional assessments. The IPCC cautions that "there are many uncertainties in our predictions particularly with regard to the timing, magnitude and regional patterns of climate change." They go on to say that the "confidence in the regional changes simulated by GCMs remains low." Therefore, one must consider the following predictions of the effect of climate change in Washington as speculative. Nevertheless, speculation is important to provide the policy maker with some notion what climate change **may** have in store for the state.

Human Health and Comfort

The first area of concern is human health and comfort. Using historical weather-mortality relationships, Nichols et. al. found that hot weather had a large mortality effect on northern and mid-west cities. In the south, where high temperatures are the norm, the effect was much smaller. In addition, they found that early summer high temperatures had a larger effect than late summer highs. The authors concluded that temperature "shocks" are an important factor in mortality and that humans acclimate to heat stress conditions. Table 2 presents Nichols' estimates of climate change induced heat related mortality for several cities.

Nichols also observed threshold temperatures above which mortality significantly increases. Kalkstein and Davis corroborate this observation and reports Seattle temperature thresholds of 32·C for the summer and 3·C for the winter. Thus, if global climate change elevates summer temperatures above 32·C, one would expect increased mortality in Seattle. On the other hand, a reduction in winter time temperature excursions below 3·C, would decrease expected mortality.

While these findings underscore the health consequences of temperature extremes, there are three mitigating factors. First, in a process

The Evolving World

When considering the consequences of climate change, one problem is to separate natural evolution from anthropogentic change. The very name "climate change" suggests our climate is static when, in fact, it is not. For example, from 600 to 1250 AD—the *Medieval Optimum*—Europe was warm. During this time Greenland was colonized and vineyards were cultivated in England. A *Little Ice Age* occurred between 1500 to 1850. Cold winters, reduced agriculture production and frozen canals characterized this period. Projecting consequences of global climate change in the face of such intrinsic change is extremely problematic.

Moreover, society is also changing and at speeds which exceed our ability to contemplate life 100 years in the future. Imagine the 1900 futurist predicting computers and other electronic devices, moon travel, nuclear energy or nuclear weapons, plastics, genetics, antibiotics and other medical advances. Moreover, people will adapt to climate change as they do with all changing circumstances.

The environment also evolves. Northwest paleontology studies reveal an evolving assortment of species and plants. Most plant communities are transient, seldom lasting for more than 2,000 to 5,000 years (Franklin). Agricultural crops also evolve. The National Academy of Sciences reports a ten years lifetime for any particular strain of major US agricultural crop.

Looking further back in time Benton reports tremendous changes in biological diversity. *"The diversity of all organisms increased rapidly during the Vendian and Early Cambrian to a global diversity of 280 families, then* known as mortality displacement, Nichols' analysis suggests that 20 to 40 percent of the people who died during heat waves would have died soon afterward even if the heat wave had not occurred. Second, the temperature record over the past 100 years suggests that the observed 0.5·C temperature change resulted from rising nighttime rather than daytime temperatures.(12) A limited mortality effect should result if climate change continues to manifest itself in this way. Finally, both Nichols and Kalkstein indicate a high degree of acclimation to temperature. For example, summer and winter mortality temperature thresholds for Phoenix and Minneapolis are 45·C and -20·C, respectively. Acclimation of Seattle's population to a warmer temperature regime would reduced the mortality consequences of climate change.

fell to 120 families in the Late Cambrian, and increased during the Ordovician to about 450. Diversity rose gradually from 450 to 600 families during the Paleozoic, fell to 420 families at the beginning of the Triassic, then rose rapidly to 1260 families at the end of the Cretaceous..." Gould concludes that *"[m]ass extinctions have been recorded since the dawn of paleontology."* and opines that such extinctions removed competitors to our biologic ancestors.

Table 2 Estimates of Heat Related Mortality With Climate Change†

City	Present Mortality	Temperature Rise	
		2°C No Acclimation	Some Acclimation
Chicago	173	177	88
Cincinnati	42	378	189
Kansas City	31	330	212
Minneapolis	46	209	105
San Francisco	27	66	49

† From Nichols et. al., "Possible Human Health Impacts of a Global Warming,"

Indirect health effects are less certain. It is probably correct to assume that disease vectors (e.g., ticks, mosquitoes) now confined to the tropics will spread into more temperate regions with global warming. Much less certain is how the diseases they carry will respond to the newly invaded areas. Bacteria, viruses and fungi are all affected by atmospheric conditions. Climate change may enhance or diminish the range and fortitude of these organisms. As one example, the Asian tiger mosquito, a vector of both dengue and yellowfever, was accidentally introduced into the southern U.S. The mosquito has now spread extensively to the east and north. However, this vector has yet to transmit either disease to man. Unfortunately, similar circumstances in Brazil brought about an outbreak of dengue (Rogers and Packer).

According to Dobson and Carper, the effects of tropical pathogens are likely to become worse as they move into a warmer and more humid temperate zone. Patz agrees *"The spread of infectious diseases will be the most important public health problem related to climate change"* (quoted by Stone). However, Hayes and Hussain could not statistically validate a temperature-disease relationship. They found neither a strong nor consistent relationship between temperature and the diseases tuberculosis, lyme disease, pertussis, malaria or typhoid fever. It is unknown whether a 2·C temperature rise would bring tropical diseases such as malaria, yellowfever and schistosomiasis to Washington. In any event, public health practices would likely help mitigate the prevalence and effect of these diseases should they reach this State.

Other effects of climate change on human populations include altered recreational opportunities. Recreation and tourism is especially vulnerable to climate change precisely due to its association with nature. Warming, for example would adversely affect snow skiing, while water skiing should benefit. That climate change will affect recreational opportunities in Washington is near certain. Whether the overall result is positive or negative depends on personal preferences.

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